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Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: August 1, 2014 to October 31, 2014

PI: Joseph F. Horn
814-865-6434
joehorn@psu.edu

Performing Organization:

The Pennsylvania State University

Department of Aerospace Engineering

231C Hammond Building

University Park, PA 16802

Attn: Joseph F. Horn

Phone: 814-865-6434, Fax: 814-865-7092

Email: joehorn@psu.edu

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft". The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure), aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

2. Activities this period

During the period of this report, the fully coupled integration of SFS2 (Simplified Frigate Shape 2) ship model airwake (obtained by using CRAFT Tech's flow solvers) and GENHEL-PSU helicopter simulation code has been completed. An initial coupling communication interface between CRUCNH and GENHEL-PSU has been developed using FIFO (File In File Out) approach. Initial fully coupled tests have been performed for two different cases: Hover Case I: In an open domain, Hover Case II: Over ship deck. Results have been post-processed and an abstract was submitted to the AHS Forum 71 "Simulation & Modeling" session.

Two-Way Coupling Procedure

In fully coupled solutions, blade position and aero loads are transmitted to the CFD code; the CFD code then calculates a velocity field (including the induced velocities from the aircraft airloads) and sends these velocity values back to the helicopter simulation model (Figure 1). The subsequent airloads and dynamics of the helicopter are then affected by the evolving external flow field. In this sense, the CFD solutions serve the purpose of not only the ship airwake effects but of the induced flow field generated by the helicopter main rotor (and possibly other components of the aircraft). Induced flow in the rotor is usually modeled by a lower order models in flight simulations (e.g. finite state inflow), but these modules are replaced by CFD in the fully coupled solutions. This requires a fine mesh in the vicinity of the main rotor and the wake below the rotor to avoid

excessive dissipation of the wake. This is not an efficient solution for eventual fast or real-time solutions, in which we will need to use course grids. In future applications, we will investigate simultaneous use of finite state inflow and coupled CFD flow solutions with correction factors to avoid double counting of induced flow velocities in the rotor plane.

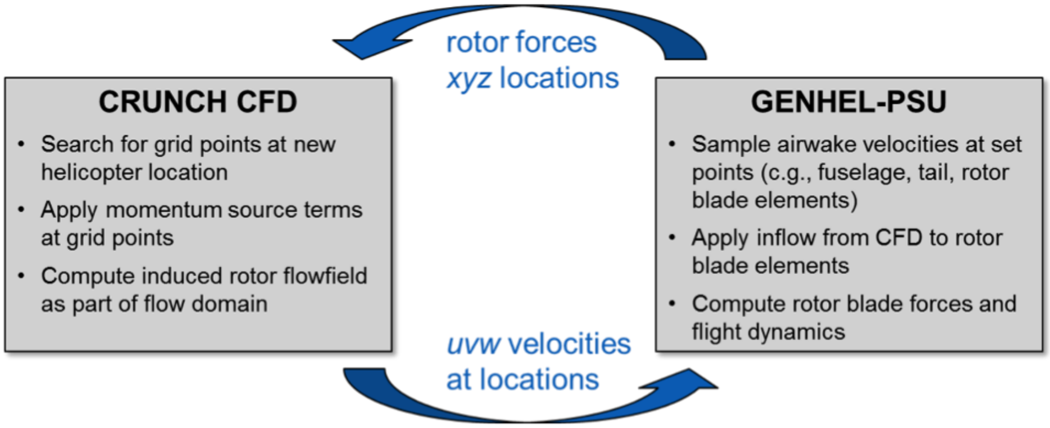


Figure 1 : CRUCNH – GENHEL-PSU communication diagram

Two different fully-coupled cases have been performed. These are:

Case I: Hover in an Open Domain

One of the initial tests on fully coupled cases has been performed with a helicopter hovering in an open domain. The GENHEL-PSU code writes blade positions and aero loads to a file, shared with the flow solver, and the flow solver returns back the velocity fields at desired locations. The coupling has been performed with tight coupling approach with a time step $\Delta t = 0.002$ sec. The parallel computing has been performed with 128 CPUs on COCOA4 supercomputer at Penn State and roughly 2000 CPU hours used for the calculations. Figure 1 show the detailed procedure of coupling interface between CRUNCH and GENHEL-PSU. This case includes three phases (Figure 2). On first phase of the analysis, simulation starts in freeze-mode, in which helicopter body is held at a specific position in the air and the rotor blades move freely. In this phase, GENHEL-PSU uses Peters-He finite state inflow model to trim and sends the blade positions and aero loads to the flow solver and ignores the velocity fields that comes back. The flow solver puts source terms to the related locations on the grid and calculates velocity fields. This phase ends when the flow solver successfully develops the rotor downwash. Two-way coupling starts in the second phase of the analysis. In this phase, the helicopter still flies in freeze-mode, but GENHEL-PSU begin to use velocities coming from the flow solver to calculate the rotor and airframe loads. This phase ends when the rotor thrust reaches equilibrium. On the last phase of the analysis, the helicopter enters free flight mode. In this mode, both helicopter and the rotor disk move freely and both of GENHEL-PSU and CRUNCH solver are coupled to each other. The controller helps to regulate the aircraft and it reaches a new hover trim condition. Figure 3 shows distribution of induced velocity on fully developed downwash and rotor disk plane. Figure 4 shows the time history change of rotor thrust after the fully-coupled simulation starts (the first 2 seconds are in freeze-mode). Figure 5 and Figure 6 show the response in position and attitude of the closed loop in no-coupling and fully-coupled hover cases. Results are similar and the controller holds the position of the helicopter within ±10 ft of the original position.

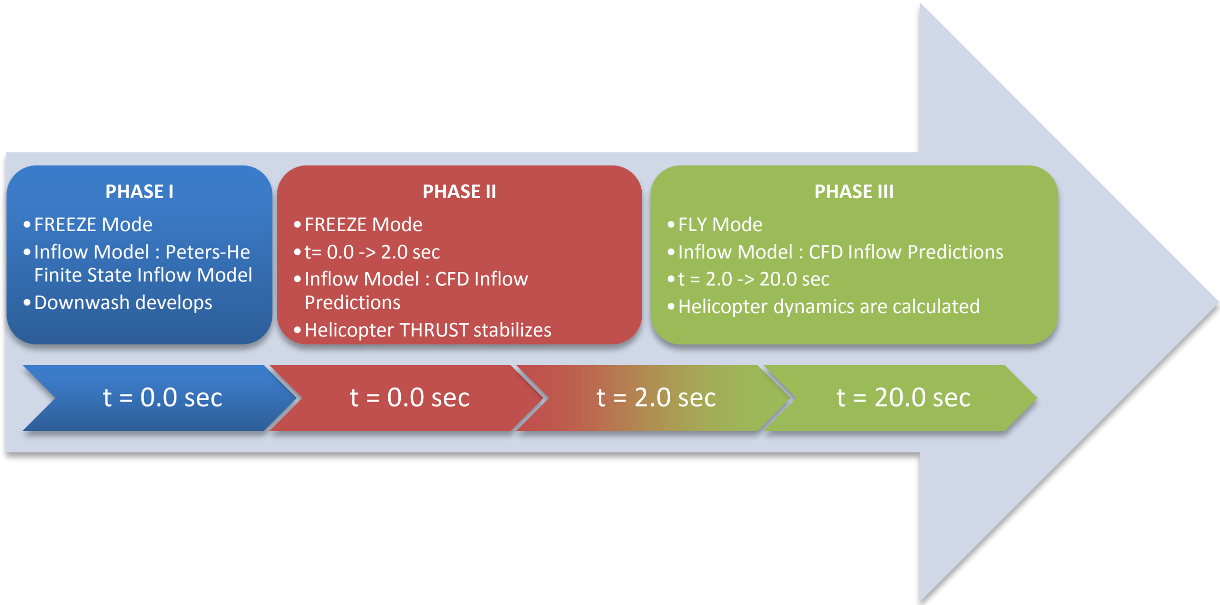
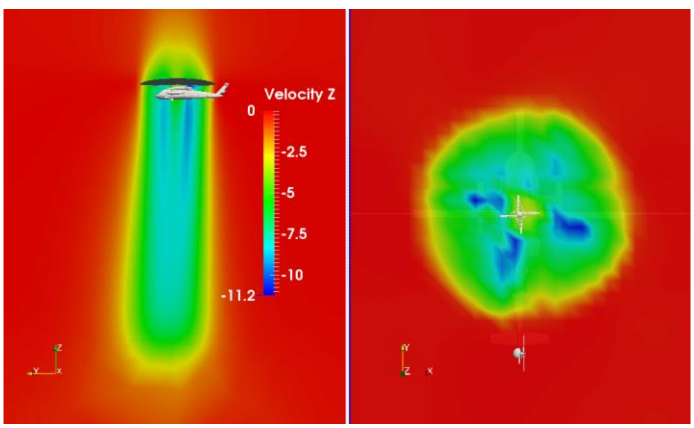


Figure 2 – Fully coupled simulation procedure



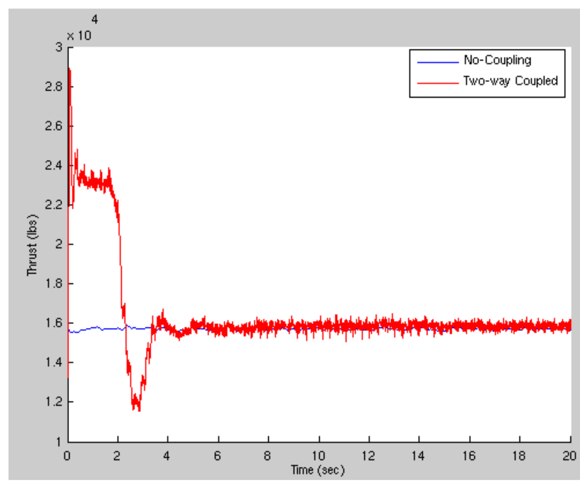


Figure 3 –Distribution of rotor induced velocity on downwash and rotor disk plane, at t=20 sec.

Figure 4 – The time history of change in rotor thrust, hover case with two-way coupled CFD rotor inflow

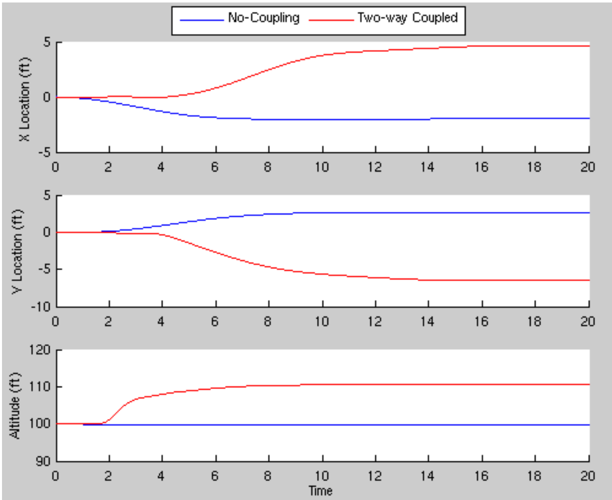


Figure 5 - Variations in positions of the simulated helicopter with TRC Controller, Hover case with Two-way Coupled CFD rotor inflow calculation.

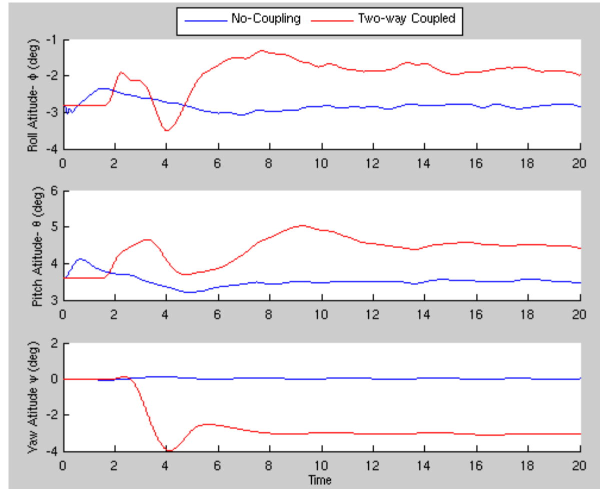


Figure 6 – Attitude response of the simulated helicopter with TRC Controller, Hover case with Two-way Coupled CFD rotor inflow calculation.

The results in Figure 3 show that the inflow develops in the CFD solver, but at the bottom of the domain the induced flow quickly dissipates. This is the region of the computational domain where the fine grid ends and the grid becomes coarser. The CFD solution was found to predict induced velocities approximately 20% lower than those predicted by momentum theory and Peters-He inflow models. Thus the initial thrust is too high, but corrected by the controller when the aircraft enters free flight.

Case II : Hover over Ship Deck

The second fully coupled test has been performed with a helicopter hovering over SFS2 ship deck. A similar procedure has been applied with Case I to perform the analysis. Similar to the Case I, tight coupling approach has been applied and both GENHEL-PSU and CRUNCH run with a time step $\Delta t = 0.002$ sec. The parallel computing has been performed with 128 CPUs on COCOA4 supercomputer at Penn State. Approximately 6000 CPU hours were needed for the simulation. Figure 7 - Figure 9 show the comparison of time averaged vertical velocities predicted by CFD solver for fully coupled and one way coupled (ship airwake database approach) hover case over ship deck at different planes. The impact of rotor downwash can be seen easily on the contour plots. The predicted rotor induced velocity changes between -0.5 m/s to -2.5 m/s, which is much smaller than both Peters-He finite state inflow model and fully coupled hover in an open domain case predictions. This difference might be a result of course grid resolution on the related area. It is oblivious that CFD solver can not resolve the inflow very well. We will investigate several approaches to solve this issue. Figure 10 shows the time history change of rotor thrust after fully-coupled simulation starts (the first 1 second is in freeze-mode). Figure 11 and Figure 12 show the response in position and attitude of the closed loop in one-way coupled and fully coupled hover cases. Results are similar and the controller holds the position of the helicopter within ±20 ft of the original position.

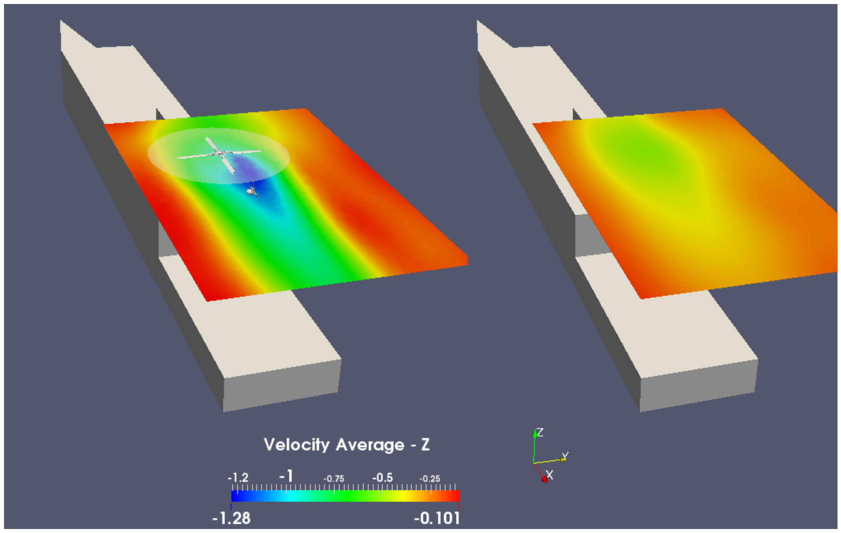


Figure 7 – Comparison of time averaged Velocity-Z, Top View, at z=77 ft

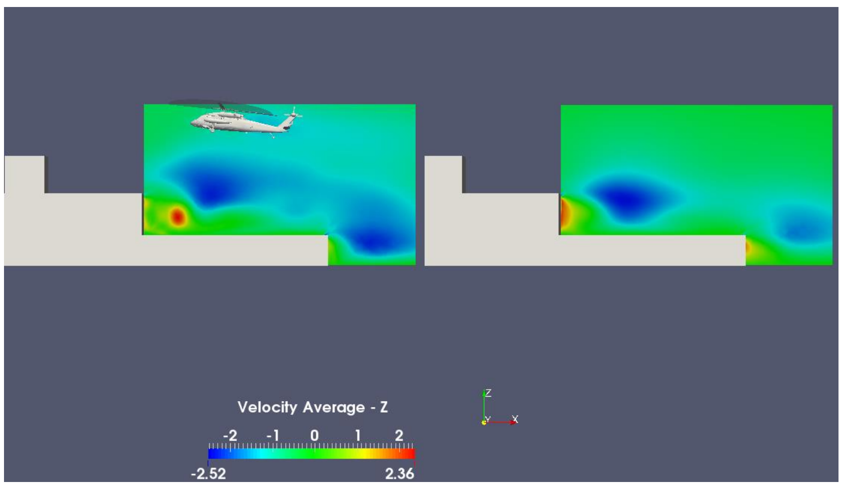


Figure 8 - Comparison of time averaged Velocity-Z, Top View, at y=-10 ft

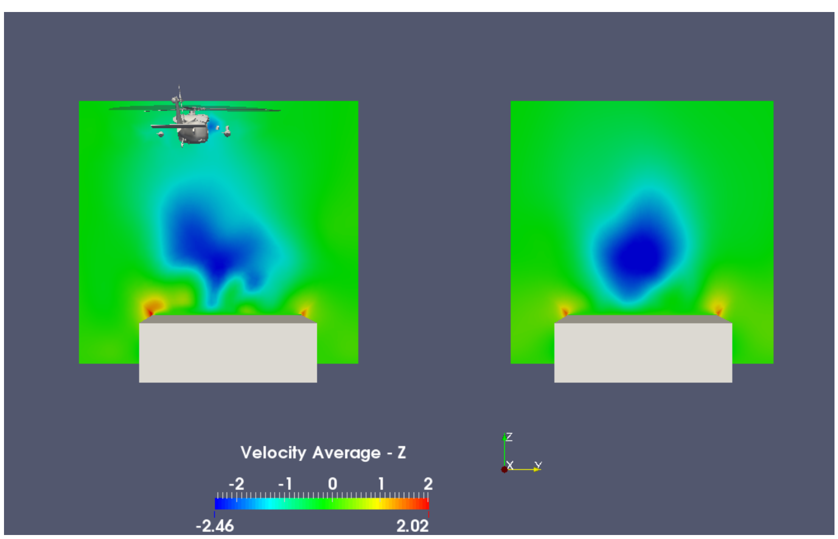


Figure 9 - Comparison of time averaged Velocity-Z, Back View, at x=403 ft

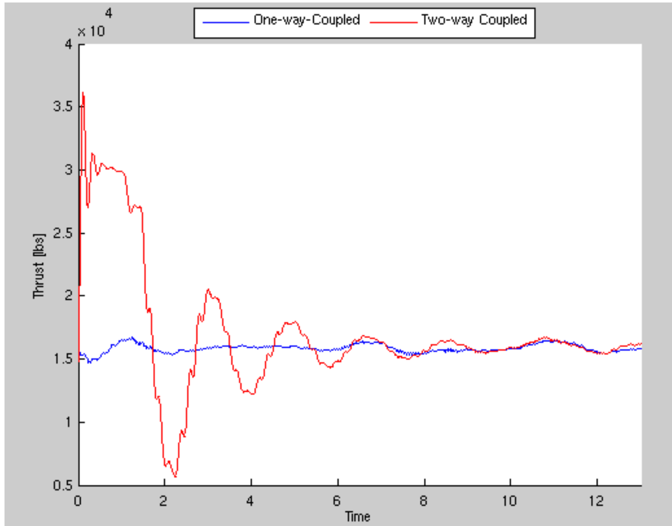


Figure 10 – Time history of change in rotor thrust, hover over ship deck

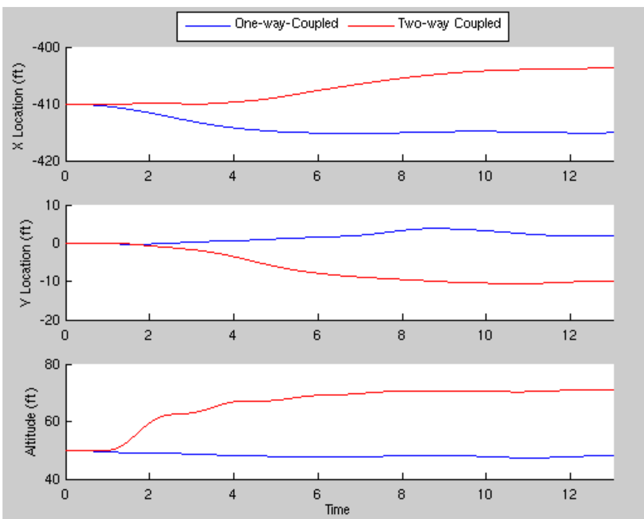


Figure 11 - Variations in positions of the simulated helicopter with TRC Controller, Hover over ship deck case with Two-way Coupled CFD rotor inflow calculation.

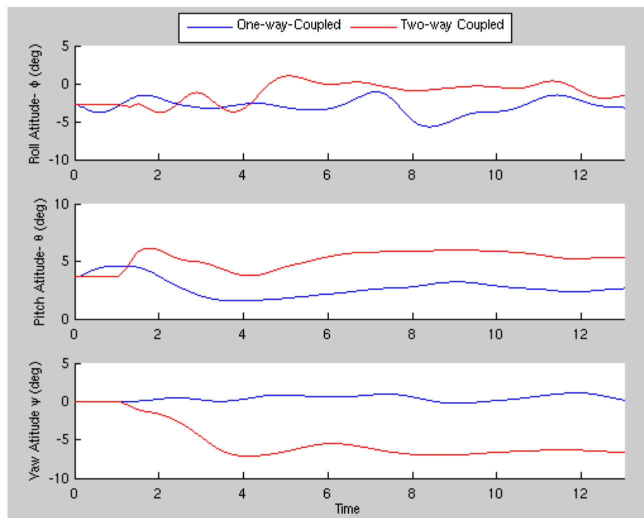


Figure 12 - Attitude response of the simulated helicopter with TRC Controller, Hover over ship deck case with Two-way Coupled CFD rotor inflow calculation.

3. Significance of Results

The results show the successful fully-coupled integration of the SFS2 airwake (obtained by using CRAFT Tech's flow solver) and GENHEL-PSU simulation code. An initial coupling interface approach between CRUNCH and GENHEL-PSU has been developed using File In File Out (FIFO). The results will provide a baseline with which to compare the faster fully coupled solutions in next stages of this study.

4. Plans and upcoming events for next reporting period

- Continue development of fully-coupled simulations: Fully-coupled simulations will be repeated with loose coupling approaches and results will be compared with tight coupled cases.
- Communication interface will be optimized for faster simulation process.

- Different inflow model approaches will be investigated for a better induced velocity prediction.

5. References

No reference was used in this report.

6. Transitions/Impact

No major transition activities during the reporting period.

7. Collaborations

Penn State has collaborated with CRAFT Tech and NAVAIR and have conducted regular discussions with them.

8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

9. Publications

An abstract with a title of "Coupled Flight Dynamics and CFD Simulations of the Helicopter / Ship Dynamic Interface" submitted to the AHS Forum 71 "Simulation & Modeling " session.

10. Point of Contact in Navy

Susan Polsky
Senior Computational Fluid Dynamics Specialist
Naval Air Systems Command Code 4.3.2.1
Applied Aerodynamics & Store Separation Branch
susan.polsky@navy.mil 301-342-8575 (Voice)

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